CRT-2000-22

Centre de recherche sur les transports (C.R.T.)
Centre for Research on Transportation

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May 2000

101-01795/

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* *This research was supported in part by the Fonds pour la formation de chercheurs et l'aide à la recherche (FCAR), and Faculty of Management, McGill University.*

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Dépôt légal – Bibliothèque nationale du Québec,
Bibliothèque nationale du Canada, 2000

ABSTRACT

We present a methodology for assessment of the hazardous materials transport risk in a multi-commodity, multiple origin-destination setting. We integrated the proposed risk assessment methodology with a Geographic Information System (GIS), which made a large-scale implementation possible. We develope a GIS-based model of the truck shipments of dangerous goods via the highway network of Quebec and Ontario. Based on the origin and destination of each shipment, we evaluated the risk associated with the routes that minimize; (i) the transport distance, (ii) the population exposure, (iii) the expected number of people to be evacuated in case of an incident, and (iv) the probability of an incident during transportation. Using these assessments, a government agency can estimate the impact of alternative policies that could alter the carriers' route choices. A related issue is the spatial distribution of transport risk, since an unfair distribution is likely to cause public concern. Thus, we also provide an analysis of transport risk equity in the provinces of Quebec and Ontario.

Keywords: Hazardous Materials, Transportation, Risk, Equity, Geographical Information Systems, Large-Scale Implementation.

RÉSUMÉ

Nous présentons une méthodologie pour l'évaluation du risque de transport des matières dangereuses dans une situation multi-commodité et plusieurs origine-destination. Nous avons intégré la méthodologie évaluation des risques avec un système d'information géographique (GIS), ce qui a donné une mise en place d'un problème de grande taille. Nous avons développé un modèle basé sur le GIS des expéditions de camion des matières dangereuses sur le réseau routier du Québec et de l'Ontario. Basé sur l'origine et la destination de chaque expédition, nous avons évalué le risque associé aux itinéraires qui réduisent au minimum; (i) la distance de transport, (ii) l'exposition de la population, (iii) le nombre prévu de personnes à évacuer en cas d'incident, et (iv) la probabilité d'un incident pendant le transport. En utilisant ces évaluations, un organisme gouvernemental peut estimer l'impact des politiques de rechange qui pourraient modifier les choix de l'itinéraire des porteurs. Une issue relative est la distribution spatiale du risque de transport, puisqu'une distribution injuste est susceptible d'augmenter le souci public. Ainsi, nous fournissons également une analyse des capitaux propres de risque de transport dans les provinces du Québec et de l'Ontario.

Mots clefs : Matières dangereuses, transport, risque, capitaux propres, système d'information géographique, mise en place d'un problème de grande taille.

Hazardous Materials Transport Risk Assessment: A Large Scale Implementation

1. Introduction

In industrialized countries, a significant portion of the materials transported is harmful to human health and to environment. Materials of this nature are called dangerous goods, or hazardous materials (hazmats). They include explosives, gases, flammable liquids and solids, oxidizing substances, poisonous and infectious substances, radioactive materials, corrosive substances, and hazardous wastes. Although rare events, accidental releases of hazmats do happen during transportation, and they often have very undesirable consequences, including fatalities. Therefore, mitigation of the associated public and environmental risk is an essential component of hazmat transportation planning.

Hazmat carriers and government agencies typically have quite different perspectives in planning the hazmat shipments. From the viewpoint of a carrier, a hazmat shipment is a means to derive profits and the regulations securing public and environmental safety are to be obeyed so as to stay in business. Whereas a government agency's primary focus is to mitigate the hazmat transport risk without posing a significant challenge to economic viability of the transportation activity. Another notable difference is the scope of the problem. Given the amount and type of hazmat to be shipped, the problem of a carrier boils down to identifying the most appropriate route between the origin and the destination. A government agency, however, has to deal with all the hazmat shipments in its jurisdiction. This typically involves assessment of the total transport risk imposed on the public by the movement of a multiplicity of dangerous goods between a large number of origin-destination pairs. It is important to note that almost all of the academic literature on hazmat transportation adopts a carrier's perspective and focuses on single commodity, single origin-destination problems.

In this paper, we adopt the viewpoint of a government agency and present a method for assessment of the hazmat transport risk in a multi-commodity, multiple origin-destination setting. We integrated the proposed risk assessment methodology with a Geographic

Information System (GIS), which made a large-scale implementation possible. In developing our GIS-based model, we had to extend the prevailing approaches for transport risk assessment. Using the proposed framework, we present an assessment of the transport risk due to the truck shipments of dangerous goods via the highway network of Quebec and Ontario. Based on the origin and destination of each hazmat shipment, we evaluated the risk associated with the routes that minimize; (i) the transport distance, (ii) the population exposure, (iii) the expected number of people to be evacuated in case of an accident, and (iv) the probability of an accident during transportation. Using these assessments, a government agency can estimate the impact of alternative policies that could alter the carriers' route choices. Another important issue, from the viewpoint of a government agency, is the equity of the spatial distribution of transport risk, since it effects public's perception about the transportation activity. Thus, we also provide an analysis of transport risk equity in the provinces of Quebec and Ontario.

The remainder of this paper is organized as follows. In Section 2, we provide an overview of the prevailing risk assessment methodology. In Section 3, we present the Quebec and Ontario data, which we compiled from a variety of sources. Section 4 provides a detailed account of the implementation phase as well as our methodological contributions. In Section 5, we analyze transport risk implications of different flow patterns. Section 6 is devoted to the analysis of spatial distribution of risk. Finally, we provide some concluding remarks in Section 7.

2. Prevailing Methodology for Transport Risk Assessment

Hazmat transport risk is a measure of the possible undesirable impact of dangerous goods movements on the public and environment. The literature on hazmat transportation is mainly devoted to providing a methodology for risk assessment and finding routes so as to minimize the transport risk. However, there are (at least) five different approaches for modeling the risk associated with a hazmat shipment:

1. Societal / Traditional Risk (e.g., Alp 1995, Erkut and Verter 1995)
2. Population Exposure (e.g., ReVelle et al. 1991, Batta and Chiu 1988)

3. Incident Probability (e.g., Saccomanno and Chan 1985, Abkowitz et al. 1992)

4. Perceived Risk (e.g., Abkowitz et al. 1992)

5. Conditional risk (e.g., Sivakumar et al. 1995)

We will focus on the first three representations of transport risk. This is due to the lack of empirical research that would enable us to construct realistic perceived risk functions, and the lack of consensus among researchers with regards to validity of the conditional risk model (Erkut and Verter, 1998). Now, we turn to the formal definition of the risk models used in this paper as well as their underlying assumptions.

In a transport network, any path P between a given origin-destination (o-d) pair would typically consist of a series of links. Empirical studies show that the likelihood of a traffic accident varies with road structure e.g., the number of lanes, and the probability of an incident, such as fire or explosion, depends on the type of dangerous good being carried. Let $p_{s,m}$ denote the probability of having an incident, involving hazmat type m while traversing a unit road segment on link s. For the ease of exposition, we will omit index m when referring to incident probabilities.

Assumption 1: p_s is constant on link s.

Note that any transport network can be redefined so as to satisfy Assumption 1. It is possible to divide a link that violates this assumption into sub-links, each with constant incident probability. Thus, the probability of having an incident on unit segment k of link s is $(1-p_s)^{k-1} p_s$. Let p_s' denote the probability of having an incident on link s, and l_s denote the length of link s. Observe that,

$$p_s' = p_s + (1-p_s)p_s + (1-p_s)^2 p_s + \ldots + (1-p_s)^{l_s-1} p_s$$
$$= \sum_{i=0}^{l_s-1} (1-p_s)^i p_s$$

Given that the incident probabilities are in the order of 10^{-8}, the following assumption is quite common in the hazmat literature:

Assumption 2: $p_s^i \cong 0$ for $i > 1$.

Without loss of generality, let $P = \{1,2,...,r\}$. The ***Incident Probability*** of a single shipment on path P is:

$$p_1' + \sum_{s=2}^{r} \prod_{k=1}^{s-1} (1 - p_k') p_s'$$

Based on Assumptions 1 and 2, the incident probability of path P simplifies to:

$$\sum_{s=1}^{r} p_s' = \sum_{s=1}^{r} l_s p_s \qquad (1)$$

Representation of the spatial distribution of population, within the geographical region of concern, is another crucial issue in hazmat transport risk assessment. A very common model in the literature is the point representation of population centers. That is, each population center is modeled as a point on the plane, and all of the people living in that center is considered to be affected from an incident if the point representing the center lies within the impact area of an incident. Traditionally, the impact area of an incident is assumed to be a circle centered at the incident location and it is called the *danger circle*. The radius of a danger circle depends on the type of hazmat being shipped. Recently, Erkut and Verter (1995) proposed an extended model, in which population centers are represented as polygons rather than points. Clearly, the polygon representation of population centers improves the accuracy of a risk assessment framework, and hence we use this approach in our analysis. Let d_s denote the population density around a unit road segment on link s.

Assumption 3: d_s is constant on link s.

Let $C_{s,m}$ denote the number of people living within the danger circle of hazmat type m around link s, and λ_m denote the impact radius of hazmat type m.

$$C_{s,m} = \pi \lambda_m^2 d_s$$

The Societal or ***Traditional Risk*** of a single shipment on path P is the expected number of people that will be affected as a result of an incident during transportation. Based on the assumptions mentioned above the societal risk of path P simplifies to:

$$\sum_{s=1}^{r} p_s' C_{s,m} = (\sum_{s=1}^{r} l_s p_s d_s) \pi \lambda_m^2 \qquad (2)$$

The ***Population Exposure*** of a single shipment on path P is the total number of people that will be exposed to the potentially hazardous vehicle. It is possible to consider the hazmat shipment over a link as the movement of the danger circle along that link. This movement carves out a band, on both sides of the link that is the region of possible impacts. We refer to that area as the *exposure zone*, and denote the exposure zone of hazmat type m around link s as $EZ_{s,m}$. Let $\overline{C}_{s,m}$ represent the number of people living in $EZ_{s,m}$. When link s is a straight line $\overline{C}_{s,m} = d_s(2 l_s \lambda_m + \pi \lambda_m^2)$

Clearly, the population exposure of path P is:

$$\sum_{s=1}^{r} \overline{C}_{s,m} \qquad (3)$$

3. The Quebec and Ontario Data

We implemented the GIS-based risk assessment framework, proposed in this paper, in analyzing the hazmat transport risk in Quebec and Ontario. We focused on truck shipments of gasoline, fuel oil, petroleum and coal tar, and alcohol. These four materials constitute 56% of all the hazmats transported via the Canadian highway network. From the records of Statistics Canada, we obtained the origin and destination of each shipment within the two

provinces in 1998. There are 251 o-d pairs for gasoline, 239 o-d pairs for fuel oil, 210 o-d pairs for petroleum and coal tar, and 75 o-d pairs for alcohol. Since the records do not contain reliable information with regards to the amount of hazmat carried, we focused on the number of shipments between each pair. Thus, we assumed that each truck carrying a certain hazmat poses the same risk regardless of the amount of its cargo. Within the two provinces there were 102,420 gasoline shipments, 70,414 fuel oil shipments, 40,566 petroleum and coal tar shipments and 4,781 alcohol shipments in 1998.

According to the 1996 population census, there are 1149 census sub-divisions in Quebec and 543 census sub-divisions in Ontario. Longeuil and Montreal are the two most densely populated sub-divisions in Quebec with 1485 and 1138 people per square kilometer, respectively. In Ontario, York and Toronto are the top two sub-divisions in terms of population density with 4540 and 4099 people per square kilometer, respectively. We focused on the census sub-divisions with a population density larger than 40 people per square kilometer. Thus, our model includes 108 zones in Quebec with a total population of 3.8 million and 72 zones in Ontario with a total population of 7.6 million.

We used the highway network of Quebec and Ontario that is provided with ESRI's ArcView 3.1. GIS software. We adopted the estimates provided by Shortreed et al.(1994) for accident probabilities (see Table 1). Shortreed et al.(1994) also suggest a 5% conditional probability for the occurrence of an incident, given a traffic accident involving a hazmat truck. That is, our p_s values are obtained by multiplying the values in Table 1 with 0.05. A link segment corresponds to an urban road if it lies within a population center and a rural road otherwise. In terms of incident type, we focus on spills that involve gasoline, fuel oil and alcohol trucks, and fires that involve trucks carrying petroleum and coal tar. For these incidents, Transport Canada (1996) requires evacuation of the people residing within 800 meters of an incident site. Thus, the undesirable consequence of our concern is evacuation of people and the impact radius used in our analysis is 800 meters.

Road Type	Urban	Rural
Multi-Lane divided	1.11	0.43
Paved Divided	1.89	0.71
Paved Undivided	2.05	0.77

Table 1: Accident frequency per million kilometers

4. The GIS-based Implementation

Representation of the population centers, the road network and the origin and destination points for the hazmat shipments constitutes the groundwork for the development of a GIS-based risk assessment procedure. GISs provide a natural environment for polygon representation of population centers. Thus, we obtained a digitized map of the 180 sub-divisions from Statistics Canada, and incorporated this as the initial layer of information. We used the latitude and longitude information in representing the origin and destination points of the shipments as the second layer. The third layer is the highway network of Quebec and Ontario. The ArcView 3.1 implementation, which we used, contains 130 links and the road type is specified for each link i.e., multi-lane divided, paved undivided, and paved divided.

The above-mentioned three layers of data need to be processed so as to construct a GIS-based model that is suitable for representing the transportation of hazmats in Quebec and Ontario. First of all, many of the origin and destination points are not on the highway network. We assumed that the trucks would be required to use the shortest routes when they are off the highway network. This is a plausible assumption within many municipalities, especially in large population centers. Thus, we projected each origin and destination point onto the closest highway link, and used the resulting points as the origins and destinations in our model. We divided the original links so that each origin and destination in our network model is an end-point of a link. The outcome of this process is a transport network with 445 links.

We had to further process the 445-link highway network, since it contains a number of links that violate Assumptions 1 and 3. We divided these links so that each link either lies in one population center or it is a rural road. The resulting transport network has 1170 links, each satisfying Assumption 1. This transformation, however, does not guarantee that the population density around each link is uniform. It is possible that more than one population center is affected by a shipment on a link. For example, as depicted in Figure 1, the exposure zone around the link in Trois-Rivieres-West also contains a portion of Trois-Rivieres.

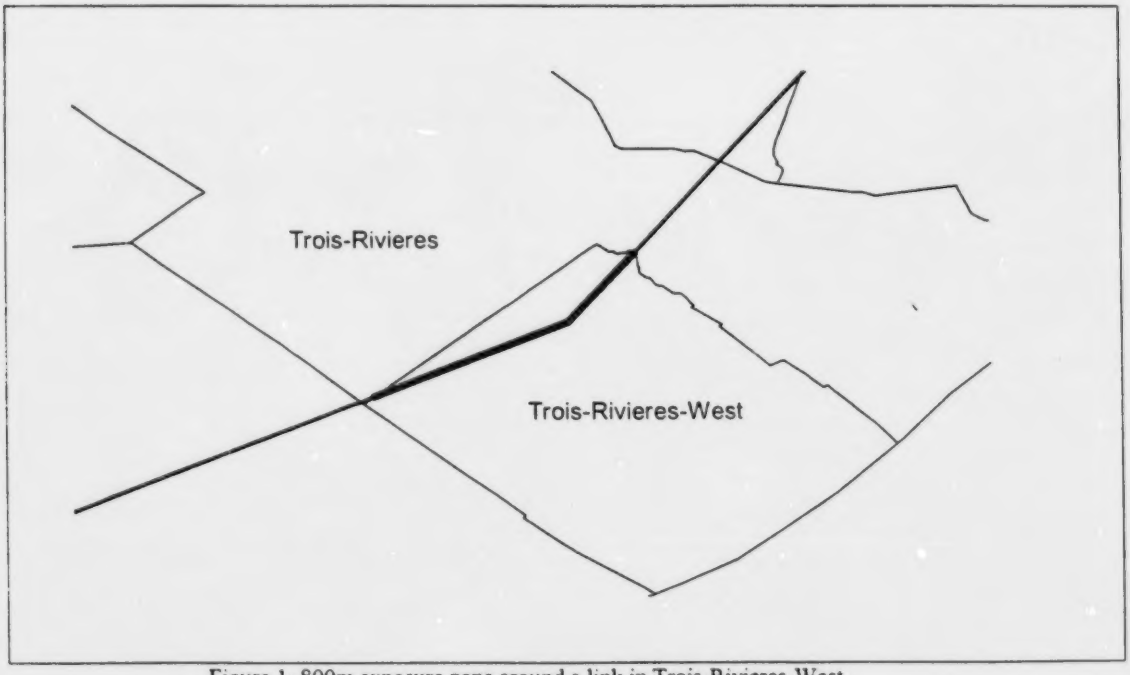

Figure 1: 800m exposure zone around a link in Trois-Rivieres-West

We calculated the weighted population density around the links that violate Assumption 3. Let d_a denote the population density of population center a and $A(a)$ denote its area. Naturally, the weighted population density of link s depends on the hazmat being shipped:

$$wd_{s,m} = \frac{\sum_a d_a \, A(EZ_{s,m} \cap a)}{A(EZ_{s,m})} \qquad (4)$$

The impact radius is the same for all four hazmats we studied. Consequently, the weighted population density around a link does not vary according to the hazmat type. Thus, there are three attributes associated with each link in our 1170-link network: p_s, l_s and $wd_{s,m}$. This GIS-based network model satisfies all the assumptions stated in Section 2, and it constitutes the framework we used in assessing the risk of hazmat transportation on Quebec and Ontario highways.

One of the powerful features of the GIS environment is the ability to calculate the area of the exposure zone around a poly-line, such as in Figure 1. Thus, we did not have to further divide the links into straight-line segments. Although the straight-line representation of road links has been used in the literature (e.g., Erkut and Verter, 1995), it would have increased the size of our network considerably. Thus, in our GIS-based model $\overline{C}_{s,m} = wd_{s,m} A(EZ_{s,m})$.

It is important to note that the Statistics Canada database contains information with regards to the origin and destination of each shipment, and the actual route that has been used is not recorded. We assumed that the carriers would use the shortest paths (MinLength) for their shipments. This assumption is quite plausible, unless a hazmat truck is trying to avoid the inspection centers on the road. As alternative routing strategies, we studied minimization of societal risk (MinRisk), population exposure (MinExpo) and incident probability (MinProb). Under each criterion, the routing problem for a given o-d pair is amenable to solution by the use of a shortest path algorithm. We used the Dijkstra (1959) implementation provided in the Network Analyst extension of ArcView 3.1. Note that $wd_{s,m} = 0$ for a significant majority of the rural roads in our model. For these links, we used the travel distance as a tiebreaker within the shortest path algorithm under the MinRisk and MinExpo criteria.

5. Transport Risk Implications of Different Flow Patterns

In this Section, we report on transport risk implications of the flow patterns associated with the four routing criteria mentioned above. In an effort to estimate the status quo, we

identified the shortest route between each o-d pair. Based on the number of shipments along each route, we calculated the number of trucks that use each road link. Thus, Figure 2 depicts the hazmat transportation activity on the Quebec and Ontario highways in 1998. The thickness of a link in Figure 2 represents the annual number of trucks that use the link.

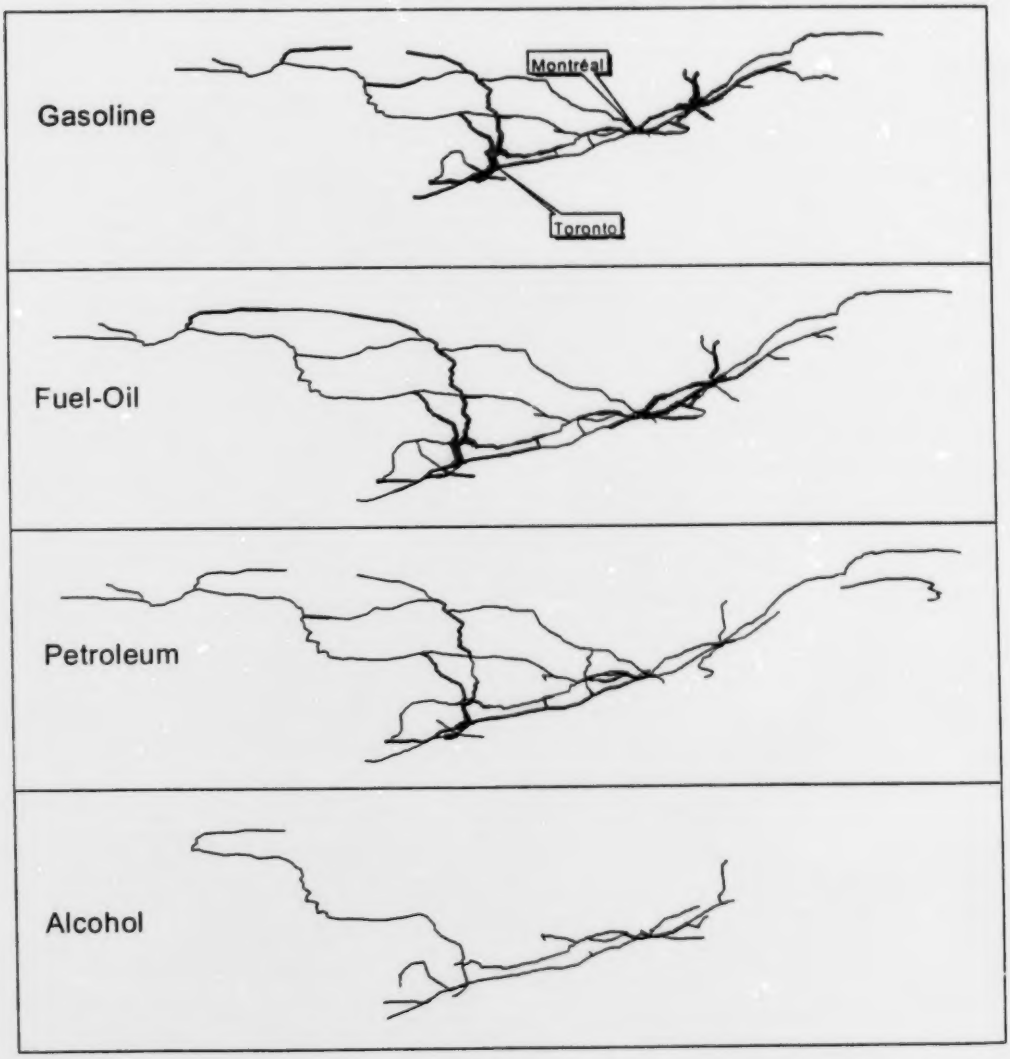

Figure 2: Flow patterns under the MinLength criterion

We also generated the flow patterns under the MinRisk, MinExpo and MinProb criteria. Clearly, the link impedances in the associated shortest path problems are $p_s{}'C_{s,m}$, $\overline{C}_{s,m}$ and $p_s{}'$ respectively. Table 2 depicts the average travel distance and population exposure for the hazmat trucks under each criterion.

Criteria	Km/truck				People/ truck			
	Gasoline	Fuel Oil	Petroleum	Alcohol	Gasoline	Fuel Oil	Petroleum	Alcohol
MinLength	230	242	212	392	73,983	100,272	88,558	164,297
MinRisk	359	550	417	962	43,839	53,144	43,225	55,181
MinExpo	437	761	488	1,139	43,207	50,104	42,451	52,993
MinProb	235	275	235	410	71,763	102,146	90,123	170,450

Table 2: Average travel distance and population exposure

On the average, alcohol trucks travel the longest distances and expose the largest number of people to risk under each criterion. From the viewpoint of total societal risk, however, these trucks cause the least concern. This is primarily due to the relatively small number of alcohol shipments. Table 3 provides our assessment of the total societal risk.

Criteria	Expected number of people evacuated				
	Gasoline	Fuel Oil	Petroleum	Alcohol	TOTAL
MinLength	545	469	237	51	1,302
MinRisk	365	266	124	19	774
MinExpo	374	286	126	20	806
MinProb	530	476	240	53	1,299

Table 3: Total Societal Risk

The most important message one can draw from Table 3 is that the expected number of evacuations can be reduced 41% by using the MinRisk criterion rather than MinLength in routing the hazmat trucks. Also, the ranking of the routing criteria in terms of their transport risk implications varies with the hazmat being shipped. For example, switching to the use of the MinProb criterion leads to a reduction in the societal risk of the gasoline shipments, whereas it causes an increase in the expected number of evacuations associated

with the other three hazmats. We will focus on the gasoline trucks for a more detailed analysis of the trade-off between the routing criteria. Figure 3 shows the gasoline flows in Quebec and Ontario with respect to each routing criterion.

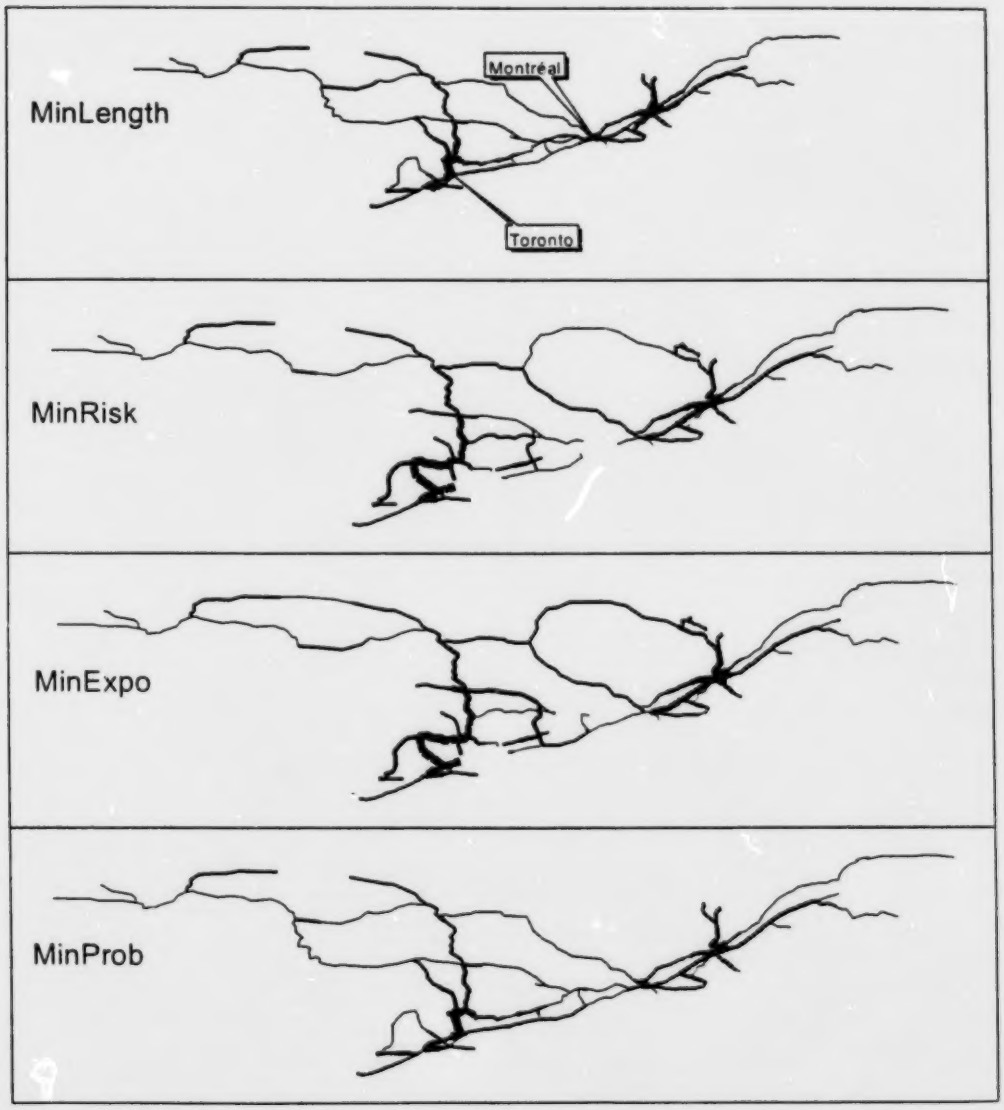

Figure 3: Gasoline Flows on the highways of Quebec and Ontario

In terms of the flow patterns, the MinLength and MinProb paths are quite similar for gasoline trucks. There is also an apparent similarity between the MinRisk and MinExpo

paths in Figure 3. These similarities can be explained on the basis of the common factors among the routing criteria. Note that travel distance is the common factor for MinLength and MinProb, whereas both MinRisk and MinExpo incorporate population density.

Table 4 depicts the trade-off between the routing criteria in terms of travel distance, societal risk and population exposure. Assuming that the carriers are using MinLength paths, the 102,420 gasoline shipments traversed a total of 24 million kilometers on the Quebec and Ontario highways in 1998. The societal risk associated with these shipments is the expected evacuation of 545 people, and the total population exposure is the equivalent of 7.57 billion people. Note that the use of shortest paths results in the highest total population exposure. On the average, 73,983 people are exposed to a gasoline truck that is routed according to the MinLength criterion. The average exposure of a gasoline truck can be reduced 41% by the use of the MinExpo criterion (see Table 2). Each gasoline truck that follows the shortest path between Simcoe County and Toronto exposes 136,830 people to evacuation risk. This number, which is the highest average exposure in our case, is reduced to 64,800 people under the MinExpo criterion.

Criteria	Total			Index		
	Distance (M km)	Expected Evacuation	Exposure (M people)	Distance (M km)	Expected Evacuation	Exposure (M people)
MinLength	24	545	7,570	1.00	1.49	1.71
MinRisk	37	365	4,490	1.56	1.00	1.01
MinExpo	45	374	4,420	1.89	1.02	1.00
MinProb	24	530	7,350	1.02	1.45	1.66

Table 4: The societal impact of gasoline shipments

The indexes in Table 4 are obtained by dividing the total values with the smallest number in the associated column. Thus, it is possible to achieve a 33% reduction in the societal risk of gasoline shipments by using the MinRisk paths rather than the MinLength paths. This would result in a 56% increase in the distance to be traveled. An important insight provided by Table 4 is that there is not much incentive to use the MinExpo criterion for routing gasoline trucks. The MinRisk paths have almost the same societal risk and population exposure and they require considerably shorter travel distances. Furthermore, it is evident

from Tables 2 and 3 that this observation holds true also for the other three hazmats included in our analysis. Table 4 re-emphasizes the similarity between the MinLength and MinProb paths. In fact, for petroleum, fuel oil and alcohol there are no gains associated with the use of the MinProb criterion rather than MinLength. Tables 2 and 3 show that the MinLength paths are superior to MinProb paths with respect to all three attributes.

6. Spatial Distribution of Risk

In the previous Section, we analyzed the trade-off between hazmat routing criteria in terms of their overall impact. Now, we turn to an analysis of the spatial distribution of transport risk. First, we provide a comparison of the two provinces, and then we present an assessment of risk equity at the level of census sub-divisions. The analysis in this Section is based on four attributes at each population center. (i) Number of people exposed to evacuation risk i.e., population residing in an exposure zone. (ii) Total distance traveled by the hazmat trucks within the population center. (iii) Total population exposure i.e., sum of the population exposure values for each link within the population center. The population exposure of a link is the number of people living in its exposure zone multiplied by the number of trucks using that link. (iv) Individual exposure, which is the total population exposure divided by the number of people living in the population center. Note that individual exposure represents the average number of trucks that a person is exposed to, and hence it can be used as a measure of individual risk at a population center.

Province	Criteria	Population in Exposure Zone	Travel in Popul. Center (M-km)	Popul. Exposure (M people)	Indiv. Exposure (Truck/Person)
Quebec	MinLength	659,943	7.6	2,620	689
	MinRisk	603,057	8.4	2,360	622
	MinExpo	542,935	9.0	2,300	605
	MinProb	611,896	7.4	2,610	687
Ontario	MinLength	1,063,966	9.6	4,960	653
	MinRisk	277,604	5.2	2,130	281
	MinExpo	234,533	5.4	2,120	280
	MinProb	1,003,375	9.2	4,740	624

Table 5: The impact of gasoline flows in Quebec and Ontario

Based on gasoline shipments, Table 5 depicts a comparison of Quebec and Ontario in terms of the four attributes mentioned above. Clearly, the province-wide values are obtained by adding up the population center attributes, except for the individual exposure values which are calculated by dividing the population exposure in each province by the population of that province. It is evident from Table 5 that the use of MinRisk or MinExpo paths rather than MinLength paths makes a big difference in Ontario, whereas the associated impact is much smaller in Quebec. In our opinion, this is due to the star-shaped structure of the highway network in Quebec, which makes it impossible to totally avoid populated areas. Note that the travel distance within population centers increases in Quebec when the MinRisk or MinExpo paths are used. This simply means that the only way to avoid heavily populated areas is to pass through less populated zones. In contrast, Ontario's highway network allows for the use of rural roads under the MinRisk and MinExpo criteria, and hence the travel distance within population centers decreases when these paths are used.

In Quebec, the maximum population in an exposure zone is observed in Montreal regardless of the routing criterion used. The number of people exposed to evacuation risk is 236,878 under MinLength, which reduces to 183,339 under MinExpo. In Ontario, the MinLength paths expose a maximum of 179,720 people (in North York). When MinExpo paths are used, however, the maximum is observed in Ottawa where 61,051 people live in an exposure zone. With regards to individual exposure, the maximum in Quebec is 4080 trucks per person (in Beauport) under MinLength, which increases to 4748 (in Sainte-Foy) under MinExpo. In Ontario, however, the maximum individual exposure is always observed in Mississauga, which is 3192 trucks per person under MinLength and it reduces to 3085 under MinExpo. It is interesting to note that none of the maximum values in Ontario is observed in Toronto, which is one of the most densely populated areas in the province.

Among the four attributes we studied, individual exposure seems to be the most appropriate for evaluating spatial distribution of risk. Figure 4 shows the individual exposure at the census sub-divisions in Greater Toronto area due to gasoline shipments. The darkness of the shading in Figure 4 is proportional to the trucks per person value. There are clear differences between population centers in terms of individual exposure to gasoline trucks,

which might raise concerns over fairness of the spatial distribution of risk. The concept of equity has been studied in the literature within the context of location of obnoxious facilities. Marsh and Schilling (1994) provided a comprehensive review of the different equity measures. Whereas, Erkut (1993) presented two equity axioms and showed that the Gini Coefficient and the Coefficient of Variation are the only measures, which satisfy both of these axioms.

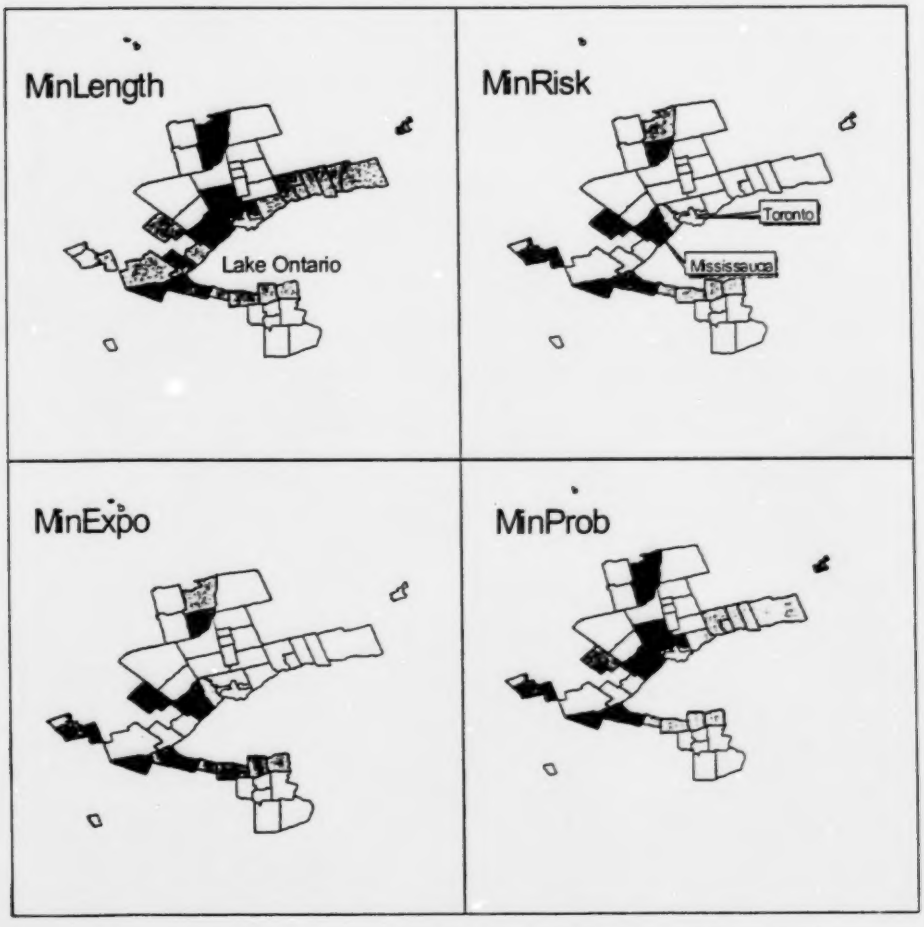

Figure 4: Individual exposure at the Greater Toronto area due to gasoline shipments

We use the two equity measures mentioned above within the context of hazmat transportation. Let t_i denote the individual exposure at population center i, n represent the

number of population centers included in the analysis, and $\bar{t}$ denote the average individual exposure. The equity measures used in our analysis can be represented as follows:

$$\text{Variation} = \frac{\sqrt{\sum_i (t_i - \bar{t})^2}}{n\bar{t}}, \quad \text{Gini} = \frac{\sum_j \sum_i |t_i - t_j|}{2n^2\bar{t}} \tag{5}$$

Coefficient of variation evaluates equity in terms of the deviation from average individual exposure at the population centers. Gini coefficient, however, focuses on the difference between individual exposure levels of each sub-division pair. Clearly, smaller values of these equity measures correspond to higher levels of fairness in risk distribution. A value of zero represents perfect equity, whereas a value of one represents absolute inequality.

		MinLength	MinRisk	MinExpo	MinProb
Quebec	**Variation**	0.192	0.181	0.185	0.196
	Gini	0.768	0.767	0.785	0.776
Ontario	**Variation**	0.243	0.352	0.341	0.246
	Gini	0.783	0.879	0.868	0.791

Table 6: Equity of gasoline transport risk distribution in Quebec and Ontario

Table 6 depicts the two equity measures for gasoline shipments in Quebec and Ontario under each routing criterion. Apparently, Variation values are much lower than the Gini values. Thus, risk distributions are fairly equitable according to the former measure, whereas they are quite unfair according to the latter. Figure 5 explains this seemingly counter-intuitive result on the basis of gasoline shipments in Ontario. Note that the average individual exposure values under the MinLength and MinRisk criteria are 653 and 281, respectively (see Table 5). Most of the population centers are quite close to the average individual exposure, and hence the low Variation values. The high Gini values, however, are due to the small number of sub-divisions with high individual exposure.

Many authors have suggested that the use of MinRisk paths would lead to a deterioration in risk equity. This is precisely what we observe in Ontario. Under the MinLength criterion, there are eight population zones with more than 1000 trucks per person. This

number reduces to three when MinRisk paths are used. Note that, the case of three outlying zones is less equitable than the case of eight outlying zones, according to the equity measures we used. It is important to note that conventional wisdom does not prevail in Quebec, where the use of MinRisk paths, in fact, fosters risk equity. In Quebec, there are 13 sub-divisions with more than 1000 trucks per person under MinLength, which increases to 16 under the MinRisk criterion. Thus, the impact of transport risk minimization on risk equity clearly depends on the topology of the road network as well as the spatial distribution of population centers.

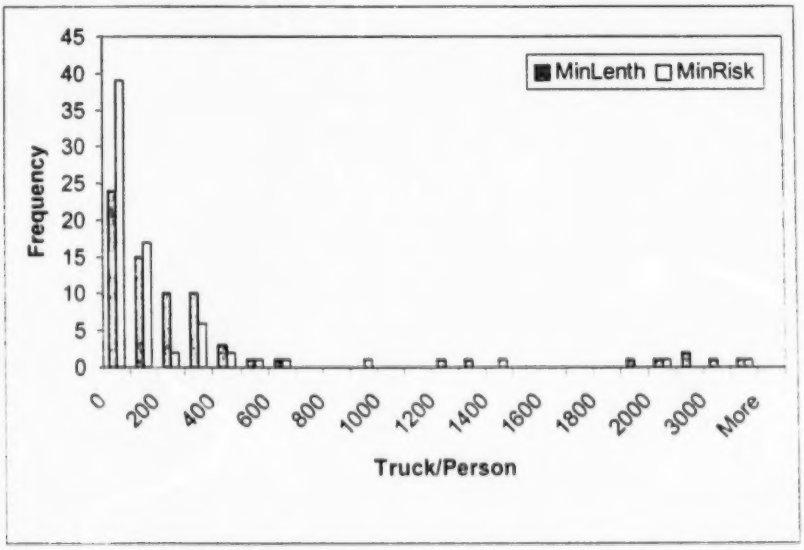

Figure 5: Individual risk in the population centers of Ontario due to gasoline shipments

Province	Criteria	Population in Exposure Zone	Travel in Popul. Center (M-km)	Popul. Exposure (M people)	Indiv. Exposure (Truck/Person)
Quebec	MinLength	708,968	17.8	6,770	1,780
	MinRisk	658,470	20.3	5,080	1,337
	MinExpo	656,008	20.5	4,780	1,258
	MinProb	708,967	17.6	6,820	1,793
Ontario	MinLength	1,063,966	23.8	12,300	1,614
	MinRisk	305,262	13.2	5,170	681
	MinExpo	265,976	13.5	5,150	678
	MinProb	1,040,142	23.6	12,200	1,607

Table 7 : The impact of all four hazmat flows in Quebec and Ontario

In closing this section, we provide Table 7, which depicts the impact of all hazmat flows in Quebec and Ontario. The conclusions one can draw from Table 7 would be in parallel with those we stated with regards to Table 5.

7. Concluding Remarks

In this paper, we present a GIS-based methodology for hazmat transport risk assessment. The distinguishing features of the proposed methodology include the polygon representation of population centers, the polyline representation of road links, and the use of a weighted population density model. On the basis of a large-scale implementation, we conclude that the transport risk in a geographical region heavily depends on the types of hazmat being carried, the topology of the road network as well as the spatial distribution of population. Thus, it is quite unlikely that general rules of thumb can be established with respect to the trade-off between hazmat routing criteria. However, the proposed methodology facilitates an analysis of the nature of this trade-off in each case. This enables us to develop a concrete understanding of the transport risk implications of different routing criteria within the pre-specified region. From a methodological perspective, we suggest that there is a need for the development of more adequate equity measures for hazmat transport risk. Note that the prevailing equity measures deteriorate when the number of population centers with high individual risk is decreased. This may not truly reflect the preferences of many of the stakeholders in the field of hazmat transportation.

The proposed methodology can be useful to a government agency in the process of developing policies with regards to dangerous goods shipments. In this paper, we report on an implementation focusing on the hazmat trucks in Quebec and Ontario. Our analysis shows that it is possible to achieve significant improvements in Ontario's public and environmental safety, by making policies that would lead to an increase in the use of routes with less transport risk. In Quebec, however, improvements of an equal magnitude would be possible only with the construction of new road segments that avoid heavily populated areas.

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